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A Procedure to Estimate the Response of Aquatic Systems to Changes in Phosphorus and Nitrogen Inputs

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Cover photo: **Heavy growth of filamentous algae in a small stream** (courtesy of Eugene B. Welch, Professor Emeritous, Environmental Engineering and Science, University of Washington, Seattle.)

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Acknowledgments

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Introduction

This document provides a simple assessment procedure to estimate the responsiveness of a waterbody to changes in the supply (loading) of phosphorus (P) and nitrogen (N). Lakes, rivers, streams, and estuaries may be assessed with this procedure. Few data about the waterbody are required. The procedure consists of a dichotomous key that leads to classifying the waterbody in question according to key characteristics that influence the responsiveness of the waterbody to changes in nutrient loading.

The assessment procedure results in the following information:

- An estimate of the responsiveness of the waterbody to increases in P or N loading
- An estimate of the responsiveness of the waterbody to decreases in P or N loading
- A description of key processes for the waterbody and suggestions for management
- Suggestions for further analysis

This procedure provides a first level screening analysis. It may be used to identify sensitive waterbodies as part of applying a Phosphorus Index-type planning tool. This procedure may be used in a watershed planning context to evaluate waterbodies as part of setting priorities. Finally, this document will be useful to landowners seeking a better understanding of how nutrients affect surface water.

The relationship between water quality and nutrient loading is complex and the results of this analysis will have a high degree of uncertainty. Nonetheless, it provides the best tool available for conservationists in the field to use in situations where little data exist. This screening procedure does not determine the nutrient loading rates necessary to protect a waterbody from degradation or to restore a waterbody to specific water quality objectives. To more accurately estimate responsiveness and to determine protective loading rates, the user should consult a professional limnologist.

A primer on eutrophication

Nutrients are necessary for aquatic ecosystems to support plant growth and the rest of the food web. However, excessive availability of nutrients is detrimental. The principle adverse impact of nutrient enrichment is to change the *trophic state* of a waterbody. Trophic state refers to the overall level of nutrients and related algae and plant growth within the system *(primary productivity and biomass)* and the relationship of primary productivity to animal growth *(secondary production).* A human-induced increase in trophic state is called *cultural eutrophication* or eutrophication for short. Eutrophication has many adverse impacts.

Excessive algae and plant growth can lead to depletion of the oxygen that is dissolved in the water. Water can hold only a limited supply of dissolved oxygen (DO) and it comes from only two sources—diffusion from the atmosphere and as a byproduct of photosynthesis. Excessive growth leads to depletion of DO because of nighttime respiration by living algae and plants and because of the bacterial decomposition of dead algae/plant material. Depletion of DO adversely affects many animal populations and can cause fish kills.

In addition to low DO problems, excessive plant growth can increase the pH of the water because plants and algae remove dissolved carbon dioxide from the water during photosynthesis thus altering the carbonic acid - carbonate balance. Because plants and algae provide food and habitat to animals, the relative abundance of species affects the composition of the animal community. Eutrophication can impart taste and odor problems to drinking water supplies and increase the costs of treating drinking water. Wastewater dischargers to waterbodies with eutrophication problems must often install higher levels of wastewater treatment at dramatically increased cost.

Finally, eutrophication interferes with recreation and aesthetic enjoyment of water resources by causing reduced water clarity, unpleasant swimming conditions, objectionable odors, blooms of toxic and non-toxic organisms, interference with boating, and "polluted appearances." The economic implications of eutrophication are significant for many communities.

Waterbodies are categorized by trophic state as follows:

Autotrophic—Systems in which primary production equals or exceeds secondary production and respiration. These systems are generally divided into the following four classes:

- ***Oligotrophic***—Systems that have low supplies of nutrients. The term means poorly nourished. Oligotrophic lakes are typically clear. Bog lakes that receive little nutrient input because of a limited catchment are oligotrophic although they may have a large standing crop of plant biomass and poor water clarity.
- ***Mesotrophic***—Systems that have intermediate nutrient supplies between oligotrophic and eutrophic.
- ***Eutrophic***—Systems that have a large supply of nutrients. The term means well nourished.
- ***Hypereutrophic***—Systems that have very large supplies of nutrients.

Heterotrophic—Systems in which secondary production and respiration exceeds primary production. These systems must have an outside source of chemical energy. Forest streams in which leaf litter is the main energy source are heterotrophic.

In the mid-1800s, the German agricultural chemist Justus von Liebig published a series of books on the relationship between nutrients and plant production. In essence, Liebig proposed that the yield of a given plant species should be limited by the nutrient that is present in the least amount relative to its demands for growth. This concept became known as Leibig's Law of the Minimum. In aquatic systems, the nutrient that is generally limiting is P or N. In most freshwater, P is the limiting nutrient. Estuaries, hypereutrophic freshwater, and certain rare freshwater systems are often N-limited.

Tables 1 through 3 provide descriptions for various waterbody types of the different trophic states and associated water column nutrient concentrations and other characteristics. The nutrient concentrations can be viewed as water concentrations at which the nutri-

Table 1 Trophic state and associated characteristics in lakes

Trophic state	Total nitrogen (ug/L) 1/	Total phosphorus (ug/L) 1/	Chlorophyll-*a* (ug/L) 1/	Secchi depth (meters)
Oligotrophic	<350	<10	<3.5	>4
Mesotrophic	350 – 650	10 – 30	3.5 – 9	2 – 4
Eutrophic	650 – 1,200	30 – 100	9 – 25	1 – 2
Hypereutrophic	>1,200	>100	>25	<1

1/ Micrograms per liter or parts per billion.

Table 2 Trophic state and associated characteristics in periphyton-dominated streams that have low water velocity 1/ (Dodds, Smith, & Zander, 1997)

Trophic state	Total nitrogen (ug/L) 2/	Total phosphorus (ug/L) 2/	Chlorophyll-*a* (mg/m^2)
Eutrophic	>300	>20	>150

1/ Higher water velocity (>15 cm/s) enhances nutrient uptake, and the thresholds for such systems would be lower (around 10 ug/L total P or 3-4 ug/L soluble reactive P).

2/ Micrograms per liter or parts per billion.

Table 3 Trophic state and associated characteristics in estuaries

Trophic state	Total nitrogen (ug/L) 1/	Total phosphorus (ug/L) 1/	Secchi depth (meters)
Mesotrophic	<500	<10	6
Eutrophic	500 – 1,000	10 – 50	2
Hypereutrophic	>1,000	>50	<1

1/ Micrograms per liter or parts per billion.

ent would be limiting the further growth of algae. These concentrations can be taken only as rough guidelines because, as we will see, many factors influence the relationship between nutrient concentrations and trophic state. For example, systems dominated by vascular plants rooted in bottom substrata are less influenced by the concentration of nutrients in the water than are systems not dominated by vascular plants. (Vascular plants have their own internal system for moving nutrients around, somewhat like our own bloodstream. Algae, by and large, do not have this internal transport system.)

One of the challenges in evaluating trophic condition is determining what the trophic state should be. Water quality goals may conflict. For example, the aesthetically pleasing, clear, blue water of oligotrophic lakes is usually associated with low fish production. Furthermore, the surrounding geology and basic hydrology typically constrain the range of achievable trophic states. The natural condition of many lakes (i.e., what would exist without any human influences) is a mesotrophic or eutrophic state. It would be futile, for example, to attempt to achieve oligotrophy in a region where the natural condition is mesotrophy.

The potential responses of aquatic systems to changing nutrient loading are shown in figure 1. As nutrient loading increases, the trophic level generally increases. At some point the system may become saturated. This occurs when the nutrient in question is no longer limiting and another factor starts to limit the growth of algae and plants. Some systems have a greater capacity to tolerate increased nutrient loading than others do. Systems with an already high loading do not respond as dramatically as systems with a low loading. Systems limited by shade or other non-nutrient factors respond less to increased nutrient loading. Lakes with long water residence times are more tolerant to increased nutrient concentration in the inflow than lakes with shorter residence times. Conversely, lakes with long residence times tend to respond more slowly to decreases in nutrient loading.

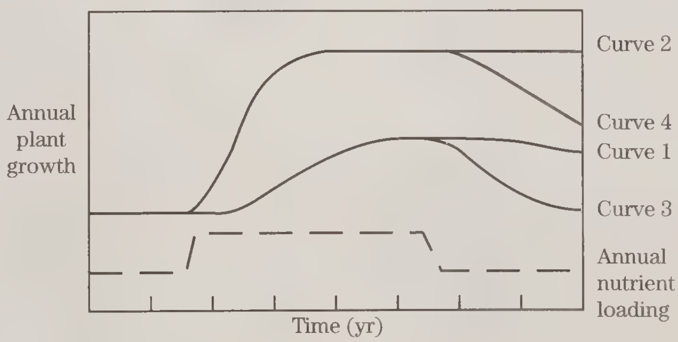
As shown in figure 1, decreasing nutrient loading does not always result in an immediate lowering of the trophic state. Nutrients may accumulate in bottom sediment, both in deposited clays and silts and deposited organic matter. In such cases nutrient release from the sediment results in internal loading of nutrients. Systems that exhibit this sediment memory have slower recovery rates after external nutrient loads are reduced than systems without sediment memory.

Aquatic systems can be classified according to the limnological characteristics that influence how they respond to changes in nutrient loading. For example, streams with extensive shading during the growing season generally are light-limited and respond less to nutrient increase than streams without shading. Well-lighted streams with water velocity greater than 10 centimeters per second (0.33 ft/s) and low nutrients are generally characterized by diatoms instead of filamentous algae and are substrate-limited. Basic physical characteristics can provide important insights into how an aquatic system functions with respect to nutrients. The evaluation procedure presented here uses a waterbody classification system based on relatively simple physical characteristics of the waterbody. Predictions about how a waterbody will respond to nutrients and advice for management are then presented based on its classification.

Factors affecting the response of aquatic systems to nutrients

The response of a waterbody to changes in nutrient loading depends on many factors. The essential factors are those that affect algal and plant abundance and biomass accumulation, such as the availability of nutrients, light, substrate for attached plants, time for growth, temperature, grazing pressure, and physical suitability. Each essential factor may be controlled by additional factors and processes. In this section we describe the factors important to an understanding of how an aquatic system functions and how it responds to changes in nutrient loading. Many of these factors are used directly in the evaluation procedure.

Figure 1 Potential responses of aquatic systems to changing nutrient loading



		Sensitivity to loading increase: Low	Sensitivity to loading increase: High
Sensitvity to loading decrease	Low	Curve 1	Curve 2
	High	Curve 3	Curve 4

As you read about these factors, you should consult the diagrams in the appendixes. The diagrams depict the transformations that can occur for P and N in aquatic systems. The transformations are depicted as **nutrient cycles.**

Dominant plant forms

Growth of aquatic vegetation is desirable in most systems to support the food chain. However, overabundance of plants disrupts processes and leads to degradation of the system.

The three basic forms of aquatic plants are phytoplankton, periphyton, and macrophytes (fig. 2). Each form has different requirements for growth and different implications for management.

Phytoplankton—Microscopic algae suspended in the water column. Their form may be single cell, filaments, or colonies of cells. Most have limited mobility and, thus, are carried with the flow of water. They must take up nutrients directly from the water. Some cyanobacteria (also called blue-green algae) can use dissolved N_2 gas as a source of N. Some cyanobacteria also have gas vacuoles that allow them to float to the surface and promote the formation of a surface scum.

Periphyton—A community of organisms, often dominated by algae but including bacteria, fungi, protozoa, and other microbes, that grows attached to a surface. Periphyton may attach to any stable surface, such as rocks, woody debris, and vascular plants. The two main types of periphyton–associated algae are filamentous and nonfilamentous. Filamentous periphytic algae are composed of many cells linked together forming long strands. Nonfilamentous periphytic algae grow as single cells or colonies attached to bottom substrata. Nonfilamentous periphyton communities are generally dominated by diatoms.

Macrophytes—Technically, any plant large enough to be visible without magnification. More commonly, macrophyte refers to vascular plants that have roots, stems, and leaves, although in some areas mosses and liverworts are important macrophytes. Macrophytes may be rooted in the sediment or free-floating. An important characteristic of rooted macrophytes is that they obtain nutrients through their roots, translocate the nutrients to other parts of the plant, and, therefore, often depend mostly on sediment for nutrients.

The physical and chemical environments of the aquatic system strongly influence which types of plants dominate. For example, deep, turbid water does not support periphyton because light cannot penetrate

Figure 2 Aquatic plant categories (see also Terrell and Perfetti 1989)

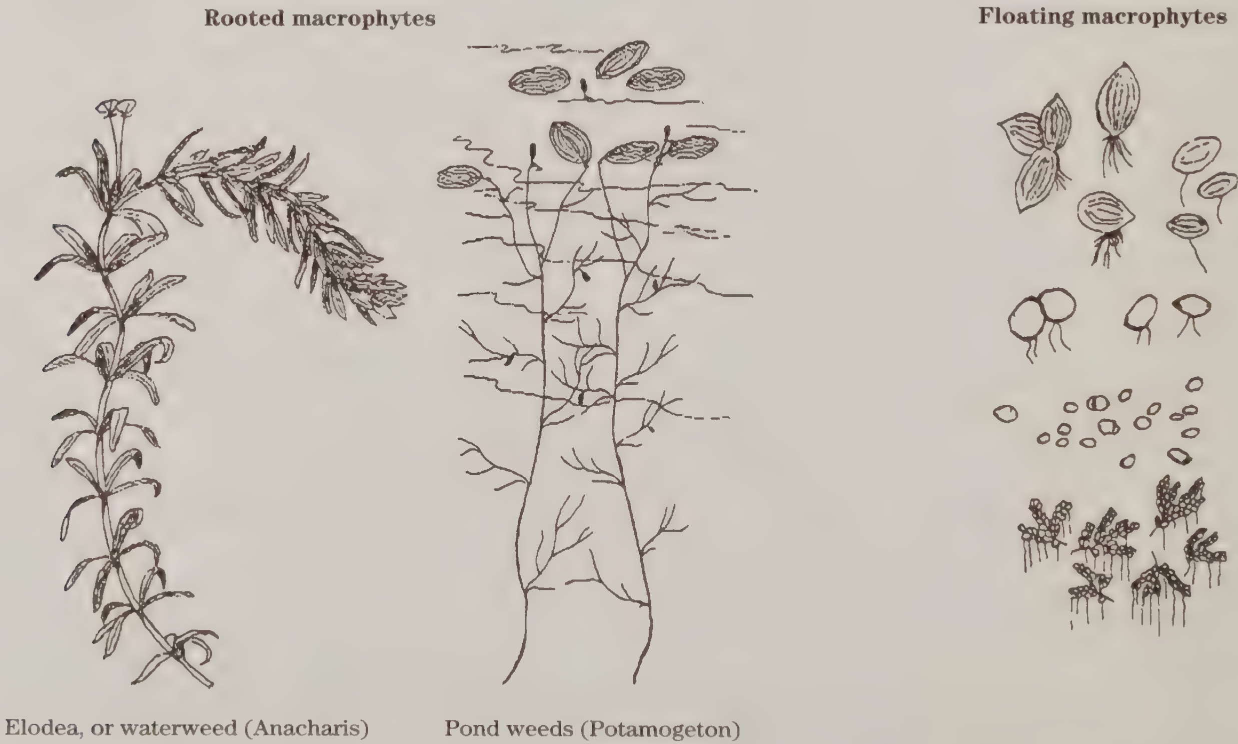
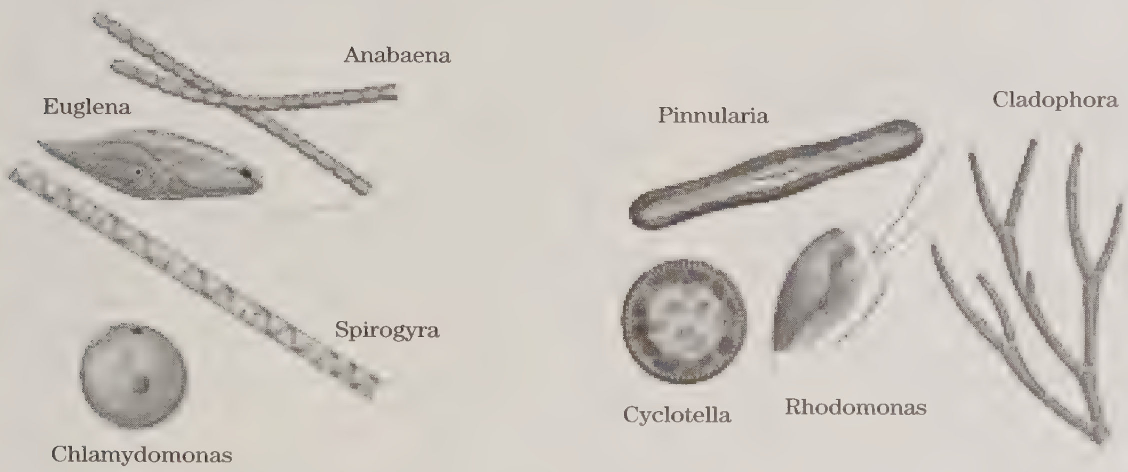
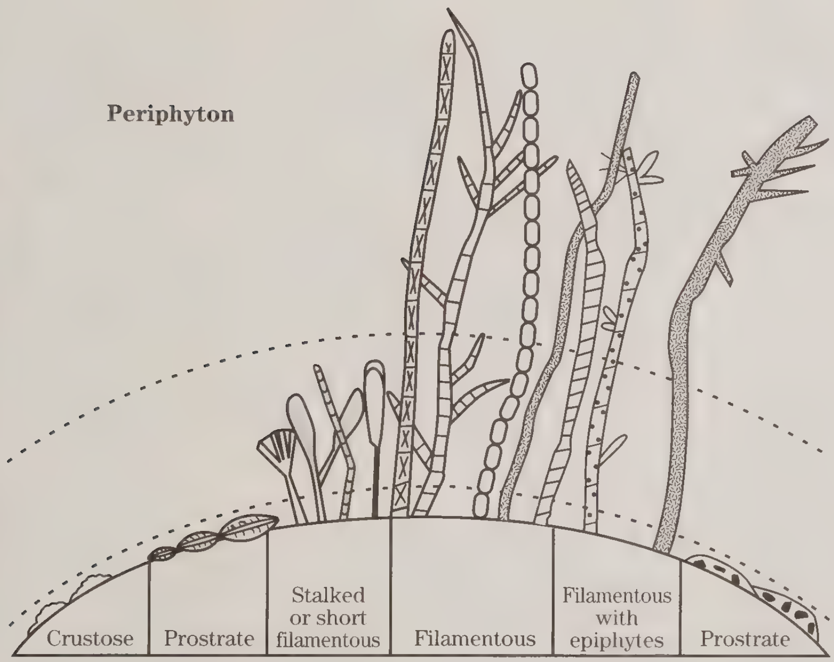


Figure 2 Aquatic plant categories (see also Terrell and Perfetti 1989)—Continued

Phytoplankton and filamentous algae



Periphyton



to the bottom, but could support phytoplankton, which would spend part of their time in the lighted zone. Rivers without sufficient residence time do not support phytoplankton because the organisms are swept away before their populations can expand.

Just as physical variables affect the kinds of plants that dominate the system, the kinds of plants that dominate influence the system's biological and chemical characteristics. For example, in favorable conditions phytoplankton populations can increase rapidly and may cause an algal bloom.

An algal bloom is a rapid expansion of an algal population that occurs when conditions are favorable. Blooms may be seen as a green coloration of the water or a surface scum if the algae are buoyant. If the bloom is large or when it dies, dissolved oxygen can be rapidly depleted. Also, some algal blooms produce toxins that can kill livestock and fish. Macrophytes can move P out of the sediment and, through dieback or grazing, release P into the water column where it is available for phytoplankton. However, macrophyte beds also stabilize sediment and reduce resuspension of sediment (and associated P) by wind-induced water turbulence. In some systems phytoplankton create sufficient turbidity to prevent macrophytes from establishing because of light-limitation. In these systems reducing water column nutrient concentrations sufficiently to control phytoplankton may lead to increased macrophyte abundance, which may lead to different impairments.

Water residence time

The water residence time of the system is an important determinant of whether phytoplankton populations can establish and accumulate. If the residence time is too short (less than 7 days), phytoplankton are swept out of the system before their populations can increase (i.e., population growth cannot overcome loss). Phytoplankton populations in such waterbodies may remain low; however, nutrient enriched water and a building population of phytoplankton may cause a problem downstream.

Residence time is measured by dividing the volume of the waterbody by the rate of flow out of the waterbody. For example, if a lake has a volume of 200 acre-feet and the flow rate at the outlet is 30 cubic feet per second, the water residence time is (200 ac-ft x 43,560 ft^3/ac-ft) / 30 ft^3/s = 290,400 seconds, or 3.4 days. For a stream, it is usually the travel time for a specific reach of the stream with some common characteristic, such as dominant land use, gradient, or substrate composition. Generally, the slower the water or the more complex the stream (e.g., lots of woody debris, braided channels), the longer the residence time. For an estuary, the residence time is the volume divided by the net loss of water per day. Lakes are more efficient traps of nutrients than are rivers, and P retention is proportional to residence time. Residence time can change seasonally as flows or volumes change.

Temperature

Most algae grow more rapidly at higher temperatures. Within the range of 0 to 25 degrees Celsius (32 to 77 °F), increasing temperature by 10 degrees Celsius (18 °F) typically doubles the rate of growth. Therefore, the response of plants to nutrient inputs during winter should be less pronounced than during summer. Blue-green algae tolerate higher temperatures than most other forms of algae.

As temperature increases, the solubility of oxygen in water decreases. For example, solubility in fresh water at 20 degrees Celsius is 9.1 mg/L, but at 30 degrees Celsius the solubility decreases to 7.5 mg/L.

Controlling temperature in streams may be a feasible algal control strategy to reduce the adverse effects of nutrients in limited situations. Water temperature rises mainly because of inputs of warmer water and direct sunlight on the water. Shade from riparian vegetation and decreasing the width-to-depth ratio are the primary strategies for lowering the temperature in streams. Shading is not a practical method of lowering the temperature in lakes, reservoirs, and wide rivers. Eliminating inputs of warm water (e.g., surface irrigation return flows) is another method.

Light

Algae and macrophytes rely on sunlight for photosynthesis and growth. In most cases plant growth rate is a function of light intensity up to some maximum, provided nutrient supplies and temperature are adequate. Light intensity is attenuated in several ways in aquatic systems.

Riparian vegetation—Riparian vegetation shades near-bank areas. Narrow streams surrounded by mature trees may be in full shade throughout the day. Well-shaded streams may have low amounts of periphyton because of light limitation, even with high nutrient concentrations.

Suspended sediment—Soil and organic particles suspended in the water column scatter light and decrease the depth of light penetration. As a result, plant

growth is limited to some maximum depth in the water column.

Color—In some systems drained by wetlands and forests, dissolved organic material, such as tannins, affects the light regime.

Self-shading—As phytoplankton or macrophyte abundance increases, sunlight penetrates less deeply into the water. As a result, at some depth in the water column not enough light is available to support plant growth and maintenance. Plants remaining below that depth too long die and decompose.

Depth

The depth of water in the system affects sensitivity to nutrient inputs. Particles in the water column scatter, reflect, and absorb light. The intensity of light decreases as depth increases below the water surface. The point at which the available light is too low to support plant growth is called the compensation point. The depth of the compensation point depends on the intensity of the light at the surface of the water and the number of particles in the water. Particles can include suspended clays, organic detritus, and phytoplankton. Areas of a lake bottom or streambed that are below the compensation point do not support periphyton or macrophytes.

In shallow (<6 ft) water, reducing suspended sediment and phytoplankton can greatly increase the transparency of the water and consequently increase the light intensity at the sediment surface. If the bottom sediment is high in nutrients, macrophytes and sometimes periphyton may establish and grow although the overlying water is low in nutrients.

Depth also is important because it is a major factor in stratification.

Stratification

Less dense water floats on top of water with greater density. In any waterbody, water layers can form according to their density. This layering is termed *stratification.* The layers do not mix with each other and chemical concentrations in one layer can be very different from concentrations in another layer. In freshwater, water temperature is the most important determinant of density. Water has the unusual property of being most dense at 4 degrees Celsius (39 °F). Because water is also a poor conductor of heat, layers of water with different temperatures (and thus, different densities) can become established and persist. In summer, warmer layers float on cooler layers and sunlight warming the top layer tends to strengthen this layering. In winter, a reversed pattern may form with water at 4 degrees Celsius (39 °F) at the bottom and colder (and, thus, less dense) water and ice floating on top.

Figure 3 illustrates temperature and dissolved oxygen profiles during summer stratification and turnover in a lake. The region of warm water near the surface is termed the *epilimnion,* the cold deep water is the *hypolimnion,* and the intermediate layer is the *metalimnion.*

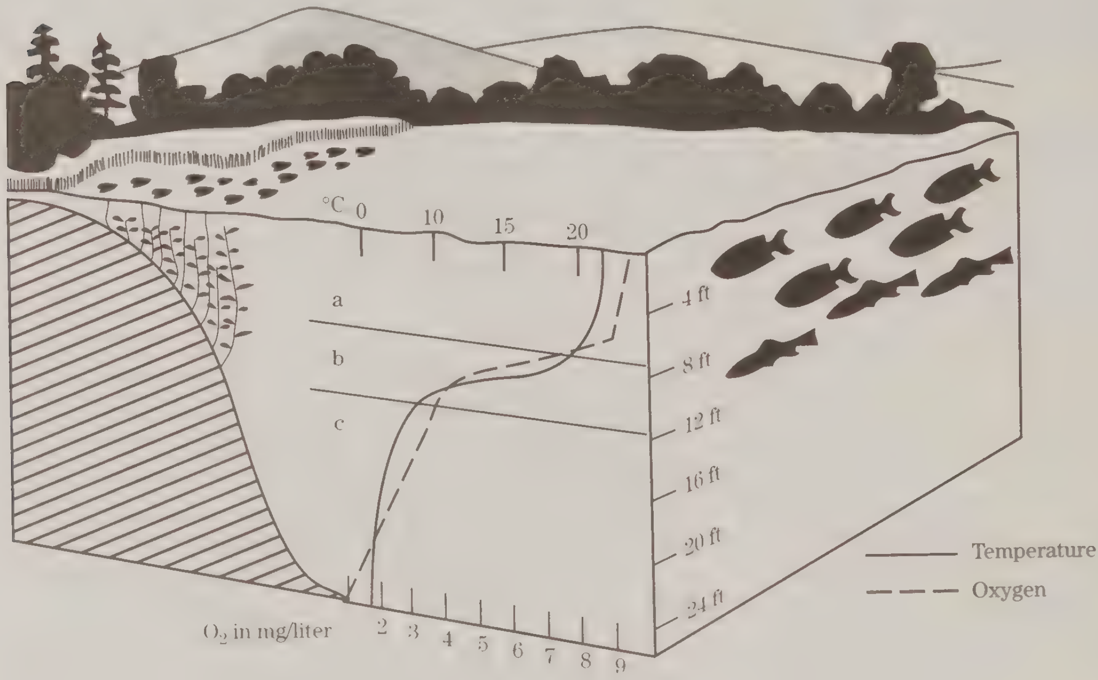
Stratification is broken down (a process termed turnover) either by turbulence or by changes in the temperature of the surface layer. Turbulence can result from waterflow (in a river) or from wind. In lakes, wind-induced turbulence can be sufficient to break up stratification if the wind is strong, there is a long fetch (i.e., length of lake surface on which the wind acts), and the lake is shallow. In temperate parts of the world, seasonal air temperature changes cause the surface layer to either cool (in the fall) or warm (in the spring) to the same temperature as the lower layer. This results in a breakdown of stratification and a turnover of the lake (fig. 3). In many areas a turnover occurs in the spring and again in the fall although not all lakes follow this pattern.

Stratification has important implications for nutrient dynamics. Because the hypolimnion is isolated from the atmosphere, dissolved oxygen in the hypolimnion may be entirely depleted by microbes decomposing organic matter in the water and in the sediment. The resulting anaerobic conditions release P bound with ferric iron in the sediment. When the stratification breaks down, the layers mix and P becomes available within the surface water where light conditions are suitable for algal growth. If conditions are right, sustained nutrient enrichment and rapid algal growth can result. However, oxygenation of the formerly anaerobic water oxidizes the ferrous iron to ferric iron, resulting in the binding and sedimentation of P. A cycle of internal release, circulation, binding, and sedimentation exists in many lakes.

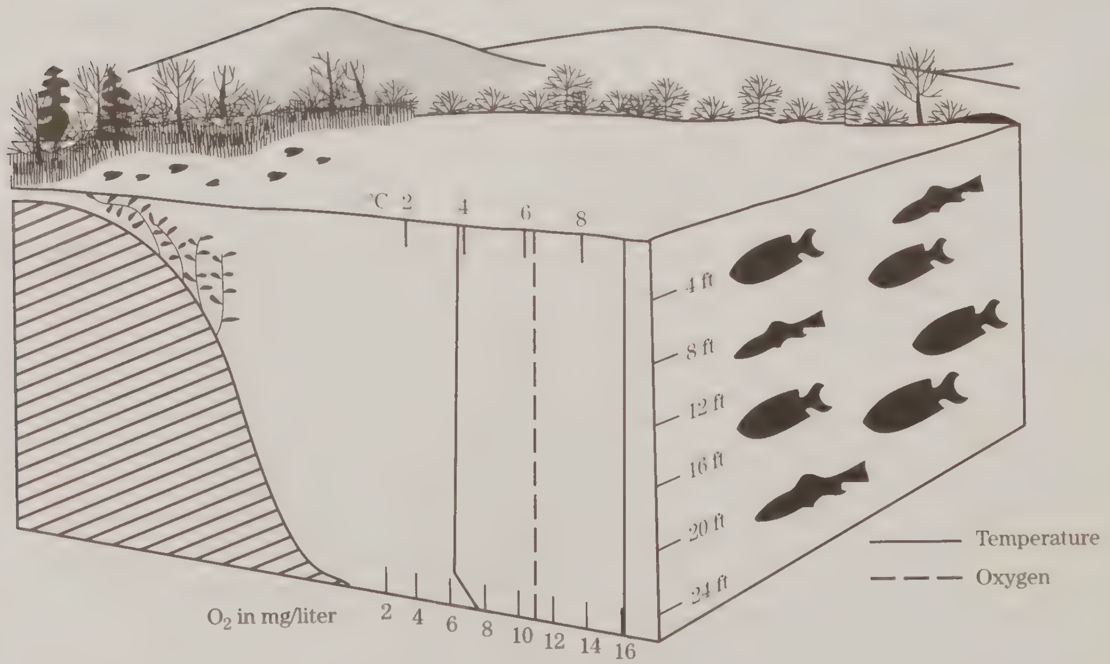
Ground water

Although most people think of a stream as being contained in its channel, a significant exchange occurs between surface water and ground water. Some sections of a stream have significant inflows of ground water (called gaining reaches), and some sections have significant outflows of surface water to ground water (called losing reaches). Even where the net gain

Figure 3 Temperature and dissolved oxygen profiles during summer stratification and turnover in a lake (epilimnion is shown by a; metalimnion by b; and hypolimnion by c)



Midsummer



Spring and fall overturn

or loss of flow is not significant, a high degree of exchange between the surface water and ground water can occur. The zone below and adjacent to the stream channel in which a mixture of surface water and ground water can be found is called the hyporeic zone.

Unpolluted ground water generally contains P and N concentrations less than 100 ug/L or ppb. Although low for N, such concentrations could represent a significant source of P. In some areas of the world, natural geological processes result in even higher concentrations of P in ground water. This natural enrichment can also occur with N, but is rare.

The temperature of deeper ground water is generally near the mean annual air temperature of a given site. As a result, ground water is usually cooler than surface water in the summer. Increasing the quantity of ground water feeding a stream, or even a small lake or reservoir, generally lowers its temperature in summer.

Forms of P and N Inputs

Phosphorus and N are carried into water in dissolved and particulate forms. In addition, N_2 gas dissolves into water from the atmosphere and can be used by cyanobacteria (blue-green algae).

Chemical analysis of water samples frequently involves measuring the dissolved and total concentrations of nutrients. Total concentrations are measured after a strong acid treatment of the sample breaks down all particles and compounds into simple ions.

Dissolved forms

The inorganic dissolved form of P is orthophosphate. Because the analytical method for measuring orthophosphate is not perfect and measures a small fraction of other forms, analytical results are often reported as soluble reactive phosphorus (SRP). Dissolved N forms are predominantly nitrate or ammonium, rarely nitrite. Both N and P can be in small dissolved organic ions as well. These nutrients can be taken up directly in some cases, while in others, the molecules or ions must be further broken down before uptake can occur.

Dissolved inorganic P and N forms are bioavailable. That is, algae and plants can absorb and use these nutrient forms immediately.

Particulate forms

The solid forms can be divided into several classes:

- ***Organic material***—The P and N in organic particles (from plant residue or manure) are held in strong bonds that are generally broken down by enzymatic processes only.
- ***Low solubility inorganic particles***—Phosphorus can occur in particles as compounds of calcium, iron, or aluminum. Under some conditions, such as low dissolved oxygen concentrations or high pH, bioavailable P may be released from these particles into the water. Nitrogen rarely occurs in low solubility inorganic particles.
- ***Adsorbed or exchangeable forms***—Some P and ammonium-N may be held on the surface of solid particles (especially clays) in forms that can enter solution readily if dissolved concentrations are lowered. These particles can be either sources of P or sinks depending on the concentration of soluble P in the water. When particles containing adsorbed P or N come into contact with rainwater (which is acidic with very low P and N), much of the adsorbed P and N is immediately released into the water.

Bottom sediment

Bottom sediment is characterized as either *rock* or *soft.*

Rock refers to bedrock, boulder, cobble, or gravel bottoms that provide a stable attachment surface for periphyton. These substrata are generally chemically stable and do not by themselves remove or add P or N to the water.

Soft sediment refers to sand, clay, organic matter, or a mixture. Sand is not very reactive chemically, and does not consolidate (stick together). Clay is a term for very fine particles (<2 microns in diameter) that generally are active in affecting the chemistry of the water. The fine clay material may remove P from the water or release P to the water, depending upon pH and orthophosphate concentrations in the water. Any iron phosphates, especially clay-sized particles, are liable to dissolve if oxygen concentrations become low.

Organic matter that accumulates in the bottom sediment is partly decomposed by microbes and releases part or all of the P and N it contains into the overlying water. Rates of decomposition are most likely to increase at higher temperatures and if dissolved oxygen is present.

Nutrient availability

Phosphorus and nitrogen are termed essential nutrients because without them organisms cannot grow or complete their life cycle. Phosphorus is required for

membrane stability, ATP, and nucleic acids (DNA and RNA). Nitrogen is important in proteins, including enzymes, and nucleic acids; plants require significant amounts for chlorophyll. At low nutrient concentrations, growth is inhibited.

In many systems the "desired condition" requires low concentrations of either P or N. In most freshwater systems, P is the most likely limiting element.

Algae and plants can obtain nutrients from sediment, the water column, and from ground water discharges into the waterbody. Additionally, atmospheric N can be converted to bioavailable N by some cyanobacteria (blue-green algae). Water column concentrations of nutrients are often useful to measure, but in some cases (noted in the system descriptions described later) water column concentrations may not be useful. The criteria for nutrient concentrations in water for different trophic states are provided in tables 1, 2, and 3.

Dissolved oxygen (DO)

Oxygen gas, dissolved in water, supports the metabolism of all aquatic plants, animals, and most micro-organisms. At 20 degrees Celsius (68 °F), freshwater in equilibrium with air (saturated with air) contains 9.09 mg O_2/L (9.09 ppm dissolved oxygen or DO). This concentration is 22,000 times lower than the concentration of oxygen in the atmosphere. Solubility, and thus the amount of oxygen in the water at saturation, decreases as the water temperature increases.

Micro-organisms, plants, and animals take up and use DO from the water. Many organisms begin to be affected adversely at DO concentrations below 6 mg/L. Microbes can eventually remove all DO from the water if the oxygen is not replenished rapidly from the air (through reaeration) or from photosynthesis (oxygen is released from algae and plants during the day).

In aquatic systems where the sediment becomes anoxic (containing no DO), processes occur that can release P into the water. In particular where sediment contains iron phosphates, iron is chemically reduced by micro-organisms from Fe^{3+} to Fe^{2+}. The Fe^{2+} form is much more soluble and, when it dissolves, the associated P enters solution as well. If O_2 enters this water again, the iron may convert back to the insoluble Fe^{3+} form and precipitate, taking some of the dissolved P with it. However, enough dissolved P may remain in solution to support relatively rapid algal growth.

Estuaries

An estuary is a body of water where river water mixes with and measurably dilutes seawater (Ketchum, 1951). Circulation patterns and mixing within estuaries are complex and are the result of salinity differences, streamflow energy, tidal effects, wind, and the geomorphology of the estuary itself. Estuaries serve several, often conflicting, societal and ecological functions. For example, estuaries support commercial and recreational fisheries. From 60 to 90 percent of the Atlantic Ocean species spend some portion of their life in estuaries (Seaman, 1988). However, estuaries are also important waterways for commercial transport and often serve as the direct recipient of processed industrial and municipal waste. Being at the downstream end of river systems, estuaries tend to receive high loads of pollutants from point and nonpoint sources.

Most observational and experimental studies have supported the general conclusion that nitrogen is the most likely nutrient to limit algal production in coastal marine environments (Boynton, et al., 1982; Smith 1998) and that estuarine phytoplankton biomass and productivity are correlated with external N inputs (Howarth 1993). However, Hecky and Kilham (1988) concluded that the evidence for N-limitation in salt water was much weaker than that for P-limitation in

fresh water. Smith (1998) concluded that the degree of N-limitation versus P-limitation of algal productivity in any given coastal marine ecosystem depends on the N-to-P supply ratio in its water. This, in turn, is a function of regional land use, population density, and hydrodynamic and atmospheric conditions. Most of the research devoted to assessing nutrient limitation in estuaries has been water-column based, and more studies are needed to assess whether the benthic plant communities respond in a similar fashion (Fong, et al., 1993).

Evaluation procedure

The evaluation procedure used in this document is based on classifying aquatic systems using a dichotomous key. At each numbered step of the key, the user is asked a question about the waterbody and given an answer couplet. Brief instructions for how to answer the question are provided — if more detailed instructions are available, that is noted. The choice that is selected to answer the question directs the user to the next numbered question in the key.

Figure 4 provides a flowchart illustrating the structure of this classification key.

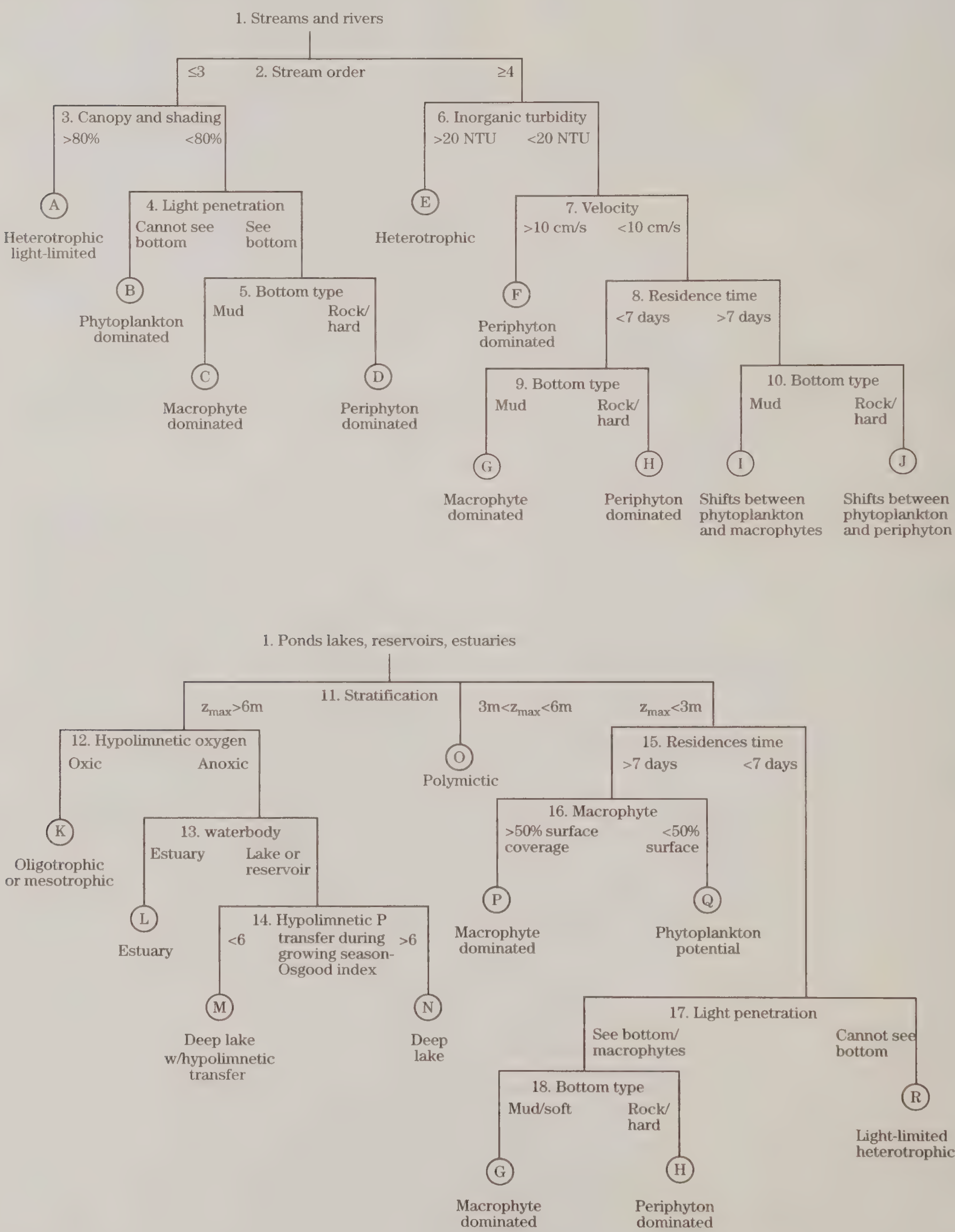
The aquatic system classification is in the form of a letter designation. Once the system is identified, turn to System Descriptions starting on page 15 for information about responsiveness, important processes, management advice, and further analysis recommendations for that system.

This evaluation should be conducted in the field because you need to make physical observations. A preliminary run through the key in the office helps to determine what equipment to bring and if any information is required that is not readily available in the field. For example, a preliminary run through the key may show that you most likely will need to know the hydraulic residence time. That characteristic would better be estimated in the office than in the field.

The first question to address before conducting an evaluation is what are the waterbodies that could be evaluated. Small lakes and ponds are straight-forward — each is a waterbody. Larger reservoirs can be more complex. Large reservoirs can have several arms that are somewhat isolated from each other and may need to be evaluated separately. River networks are the most complex for deciding what to evaluate. You should divide a river network into segments based on common characteristics of flow, shading, and depth. Each segment may need to be evaluated as a separate waterbody.

The second question to address is which waterbodies should be evaluated. The segment or waterbody that is of initial interest may not be the most critical waterbody in terms of potential impacts of nutrient load changes. Any single waterbody is likely part of a larger system, and nutrient loading changes to the waterbody being evaluated may affect a downstream waterbody. As part of the evaluation procedure, downstream waterbodies must be identified and it must be determined if they are potentially critical waterbodies for the analysis. If downstream waterbodies are likely to be highly influenced by the loading changes being examined, then the analysis procedure should be applied to the downstream waterbody in addition to the waterbody that is of initial interest.

Figure 4 Classification key structure



Finally, the user should bear in mind that nutrient loading is only one component of ecological condition. Water temperature, habitat, sedimentation, organic enrichment, and hydrology are a few of the other factors that affect water quality and ecological condition. In addition to this procedure, it may be useful to conduct a general assessment using the NRCS Stream Visual Assessment Protocol (USDA, 1998) or the Water Quality Indicators Guide (Terrell, 1989).

Classification key

1. Is the system a stream/river or not?
Streams and rivers are above the head of tide and do not include run-of-the-river reservoirs. However, rivers with low head dams that do not reduce the water velocity below what would exist in a natural pool should be treated as rivers.
Stream or river .... go to 2
Not a stream or river .... go to 11

2. What is the stream order?
See next section for instructions on how to determine stream order.
First, second, or third order .... go to 3
Greater than third order......................... go to 6

3. What is the percent canopy shading?
Percent canopy shading is measured from the center of the stream. Looking up, what percent of the sky is blocked by canopy? This should be estimated if trees are not in full leaf out.
Greater than 80%................................ System A
Less than 80% .... go to 4

4. How deep does light penetrate the water?
See bottom .... Go to 5
Cannot see bottom............................. System B

5. What is the bottom type?
Mud/soft .... System C
Rock/hard .... System D

6. How much inorganic turbidity is in the system?
See next section for instructions on how to determine turbidity.
Turbidity >20 NTU .... System E
Turbidity <20 NTU .... Go to 7

7. What is the velocity of the stream?
See next section for instructions on how to determine velocity.
Velocity >10 cm/s .... System F
Velocity <10 cm/s .... Go to 8

8. What is the residence time in the system?
<7 days .... go to 9
>7 days .... go to 10

9. What is the bottom type?
Mud/soft .... System G
Rock/hard .... System H

10. What is the bottom type?
Mud/soft .... System I
Rock/hard .... System J

11. What is the maximum depth?
Maximum depth >6 m .... go to 12
Maximum depth 3 – 6 m .... System O
Maximum depth <3 m .... go to 15

12. Dissolved oxygen in the hypolimnion?
See next section for instructions for this couplet.
Oxic .... System K
Anoxic .... go to 13

13. Is the waterbody an estuary or a lake/reservoir?
Estuary .... System L
Lake/reservoir .... go to 14

14. What is the Osgood index for the system?
Osgood Index <6............................. System M
Osgood Index >6.............................. System N

15. What is the mean residence time?
>7 days .... go to 16
<7 days .... go to 17

16. How much of the surface of the lake/reservoir is covered with macrophytes during maximum biomass accumulation?
>50% .... System P
<50% .... System Q

17. How deep into the water does light penetrate?
See bottom .... go to 18
Cannot see bottom .... System R

18. What is the bottom type?
Mud/soft .... System G
Rock/hard .... System H

Instructions for selected couplets

This section provides instructions for answering selected couplets in the key.

Couplet 2 – Stream order
Stream orders are counted from the headwater streams to the point where the river enters the ocean. A stream at the top of the watershed is first order, the second level down is second order, and so forth. If there is a confluence of streams of different orders (e.g., order 2 joins order 3), the new stream assumes the same order as that of the larger of the two joining streams (it is still order 3). It only increases in order (e.g., to an order 4) if the two joining streams are of the same order (e.g., both order 3). Figure 5 illustrates how stream orders are named.

The definition of stream should be seriously considered. It may start where a water channel contains flowing water for more than 6 months of the average year, for example. Generally, the higher the order, the wider and slower the stream. However, this relationship can vary greatly depending upon the nature of the landscape.

Couplet 6 – Water turbidity
This couplet asks if inorganic turbidity is greater than 20 NTU (nephelometric turbidity units). It is important to distinguish inorganic turbidity from organic turbidity. Inorganic turbidity is caused by clays suspended in the water and is yellow to light brown. Organic turbidity is caused by phytoplankton and organic material and is green or dark brown. Use a clear drinking glass or beaker to observe the color of a water sample.

Turbidity can be measured in a number of ways. A transparency tube is available from Lawrence Enterprises (about $35; www.acadia.net/h2oequip or 207-276-5746) and from Ben Meadows (www.bmeadows.com). It is filled with a water sample and, while sighting through the sample, water is drawn off until a pattern in the base of the tube becomes visible. Transparency is then read using the appropriate scale on the side of the tube. A transparency value of 30 cm roughly corresponds to 20 NTU. The best method is to use a turbidity meter. You may be able to borrow a meter or have samples tested at a sewage treatment plant, agency, college, or commercial laboratory. Volunteer monitoring groups may also have a turbidity meter. A secchi disk can also be used. A secchi disk is a weighted 20 cm disk painted with a white and black pattern (two quadrants black and two quadrants white). It is lowered into the water until the pattern disappears. The depth is noted, and the disk is raised until the pattern reappears. Secchi depth is the average of the two readings. A secchi depth of roughly 0.3 meters (12 inches) corresponds to 20 NTU.

Couplet 7 – Water velocity
In this couplet you must determine whether the stream velocity exceeds 10 cm/s (0.33 ft/s). Water velocity can be measured using an orange or a stick of wood as a float. An orange is a good object because it floats just below the surface where the maximum velocity typically exists. Using a stop watch, time how long it takes for the orange to float a measured distance, such as 2 meters (6.5 feet). If the orange takes time less than [10 x length in m] seconds, the velocity is greater than 10 cm/s. For example, if the travel length is 2 meters, a travel time of less than 20 seconds would indicate a velocity greater than 10 cm/s. Velocity measurements should be taken during the summer when plant growth is expected to occur. It should be done in at least 5 to 10 localized sections, and the average velocity calculated.

Couplets 8 and 15 – Residence time
Residence time is measured by dividing the volume of the waterbody by the rate of flow at the outlet. For a lake or reservoir, it is the volume divided by the flow rate of the stream draining it (see example on page 6). For a stream, residence time is generally the travel time for a specific reach of the stream with some common characteristic. (A reach is a section of a 00stream or river.) Residence time can change season-

Figure 5 Assignment of stream orders to a stream network

ally as flows or volumes change. Residence time should be estimated for the critical period for water quality. In most cases that is mid-summer when flows are low and temperature and light are high.

Couplet 12 – Hypolimnetic oxygen
This couplet asks whether the hypolimnion is oxic (aerobic) or anoxic (anaerobic). This is a critical factor for deep lakes. Unfortunately, it is not easily determined. A lake association, volunteer monitoring group, state agency, or local college may have monitoring data on DO concentrations. If data are not available, either conduct monitoring or continue using both responses for couplet 12. You will end up with two potential system descriptions, but the information may still be useful for your purpose.

If monitoring, the easiest method is to monitor the bottom 1 meter of the hypolimnion. If dissolved oxygen remains above 2 mg/L, the hypolimnion, and thus the surface of the sediments, is assumed to be oxic. If it falls below 1 mg/L, assume it is anoxic. Water samples should be taken during the critical period for the lake (late summer) and can be tested using an inexpensive test kit. Samples should be taken early in the morning when the lowest DO values are typically found, before photosynthesis increases concentrations.

Couplet 14 – Osgood index
The Osgood Index is defined as the mean depth (z) of a waterbody in meters divided by the square root of the surface area (A) in km^2, or $z/A^{0.5}$. It reflects the degree to which a lake or reservoir will mix because of forces of wind. Low numbers indicate a shallow, large lake that is readily mixed by wind, although during a period of calm days, it may become temporarily stratified.

The mean depth, z, is best determined by dividing lake volume by lake surface area (volume/area). However, unless a bathymetric map is available, volume may be unknown. Alternatively, z can be estimated by measuring depth along a transect across the pond or lake and averaging the values. Depth can be measured using a weighted survey tape or a depth meter (fish finder).

Aquatic system descriptions

This section provides information for each of the aquatic system types identified through the key. This information includes the sensitivity of the system to changes in nutrient loading, important aspects of the limnology of the system, management considerations, and analysis suggestions.

For all stream conditions where periphyton are important, the system responds more to changes in concentration than load. Although loads are referred to throughout, if increased or decreased loads do not result in concomitant increases or decreases in the predominant concentration during the growing season, then concentration should be considered the primary driving parameter from the nutrient supply standpoint. An increase in load without an increase in the predominant concentration could occur if the load increase is associated only with, for example, storm runoff. In this example the periphyton would experience no concentration change or a higher concentration for only a short period.

System A—Heterotrophic small stream

	Increased loading	Decreased loading
Phosphorus	Insensitive	Insensitive
Nitrogen	Insensitive	Insensitive

System functioning: These streams are typically light limited because of heavy shading from trees. The lack of direct sunlight prevents aquatic plants from growing, and the aquatic biological community derives energy from outside food sources, such as leaf litter. These systems are not sensitive to changes in inorganic nutrient loading, but may be sensitive to other pollutants, such as DO-depleting substances (manure and ammonia), acid mine drainage, sediment, oil and grease, and toxic substances.

Management considerations: Maintenance of the riparian vegetation and the shading provided by the riparian vegetation is essential. Maintaining access of the stream to its flood plain is also important. Hydrologic changes and excess sediment loads may cause channel widening that eventually displaces the riparian vegetation and reduces the amount of shading of the stream.

Monitoring and further analysis: There is little need for monitoring beyond channel morphology and riparian condition.

System B—Phytoplankton-dominated small stream

	Increased loading	Decreased loading
Phosphorus	Sensitive	Sensitive
Nitrogen	Potentially sensitive	Potentially sensitive

System functioning: With little shading along the streambanks, adequate light is available to support significant phytoplankton growth if nutrient concentrations are in the mesotrophic/eutrophic range and stream velocity is low. Although most streams are P-limited, in rare cases N may be the limiting factor (if background P is naturally high and N concentrations are low, such as is sometimes the case for undisturbed forest).

Management considerations: Nutrient load reduction will reduce algal biomass and related water quality problems if present. Note: If phytoplankton abundance is decreased in these systems, such that light can penetrate to the bottom, the system may shift to C or D.

Monitoring and further analysis: Water column total P is a valid characteristic to monitor in these systems. Values should be compared to the lake thresholds in table 1.

System C—Macrophyte-dominated small stream

	Increased loading	Decreased loading
Phosphorus	Insensitive	Insensitive
Nitrogen	Potentially sensitive	Potentially sensitive

System functioning: These streams are controlled by submerged and emergent vascular plants and by some floating macrophytes, such as Lemna (duckweed). They may resemble wetlands. In most cases supplies of P and N from the sediment are sufficient to support macrophyte growth.

Management considerations: There may be situations where N becomes deficient. Decreasing N loads to the stream may result in gradual depletion of N in the sediment. Macrophyte growth would then be gradually curtailed. More riparian trees and shrubs can increase shading and lower temperature and light availability in the stream water.

Monitoring and further analysis: Sediment input to these streams is the most important factor to try to estimate and control. Secondarily, if there is evidence of N limitation (low N concentrations in stream sediment) it may be worthwhile to monitor N inputs to assess the feasibility of attempting N limitation.

System D—Periphyton-dominated small stream

	Increased loading	Decreased loading
Phosphorus	Highly sensitive	Highly sensitive
Nitrogen	Potentially sensitive	Potentially sensitive

System functioning: This system can respond quickly to increases in P. Because there is little sediment memory, these systems also respond quickly to decreases in P. In most cases N is not the limiting factor unless ground water P is high and N input is low as is sometimes the case for undisturbed forest.

Management considerations: Because periphyton extract all their nutrients from the water, lowering P water concentrations inhibits growth. Ground water discharge may be an important source of N and P.

Monitoring and further analysis: Because periphyton are capable of quickly extracting nutrients from the water column, monitoring growing season water column concentrations is not recommended. Ground water moving into the stream through the stream bottom may also be an important source of nutrients. Ground water concentrations can be determined using monitoring wells, but wells will not provide discharge information. Nutrient loading rates (product of concentration times discharge) from ground water can be estimated using devices to measure ground water discharge rates and collecting ground water from below the streambed or from seeps along the banks for concentration analysis. Concentrations can also be estimated by monitoring surface water concentrations during periods when algae are not growing. However, the sampling should be as representative as possible of growing season conditions.

System E—Heterotrophic large stream

	Increased loading	Decreased loading
Phosphorus	Insensitive	Insensitive
Nitrogen	Insensitive	Insensitive

System functioning: These systems are characterized by high inorganic turbidity. The water appearance is light brown because of the suspended sediment. The high turbidity prevents phytoplankton, periphyton, and rooted plant growth because of light limitation. Although aesthetically unappealing, these systems do not experience water quality problems from eutrophication. Other problems may result from the suspended sediment, however. Fish and other organisms may be adversely affected.

Management considerations: Management goals for these systems can include reducing turbidity. As turbidity is reduced, the trophic state may shift to mesotrophic or eutrophic.

Monitoring and further analysis: Water column TP measurements help estimate the eutrophication potential. Computer models are useful to estimate nutrient loading under various scenarios of suspended sediment control.

System F—Periphyton-dominated, large stream

	Increased loading	Decreased loading
Phosphorus	Sensitive	Sensitive
Nitrogen	Potentially sensitive	Potentially sensitive

System functioning: In these streams and rivers, water velocity is sufficiently high to prevent macrophytes from establishing throughout, although backwater areas may allow them to root. Two factors limit macrophyte presence—soft bottom material is generally swept away by the current, and the plants that have a high cross-sectional area and shallow roots are uprooted and washed away.

Management considerations: Because periphyton extract all their nutrients from the water, lowering water P concentrations reduces growth. However, if ground water is an important source of P, controlling nutrients in surface inputs may not be fully successful.

Monitoring and further analysis: Water column P concentration is not a useful characteristic to monitor except during periods when plants are not growing because periphyton remove P from the water column as they grow. Ground water inputs of nutrients may be important.

System G—Macrophyte-dominated large stream or lake

	Increased loading	Decreased loading
Phosphorus	Insensitive	Insensitive
Nitrogen	Potentially sensitive	Potentially sensitive

System functioning: These systems are characterized by macrophytes because residence time is not sufficient to permit phytoplankton populations to build. The muddy bottom provides good substrate for macrophytes.

Management considerations: Because macrophytes extract nutrients from the stream or lake bottom substrate, they generally are insensitive to changes in P or N inputs to the water column over the short term. Over the long term, sediment may either accumulate or release P and N until they are in equilibrium with the water column. Exceptions can occur where sediment inputs decrease while sediment losses remain constant; gradual loss of the soft substratum could result in exposure of buried hard material. This would result in a shift to system H.

Monitoring and further analysis: Water column nutrient concentrations are less useful to monitor in these systems because growth is supported by sediment sources.

System H—Periphyton-dominated large stream or lake

	Increased loading	Decreased loading
Phosphorus	Sensitive	Sensitive
Nitrogen	Potentially sensitive	Potentially sensitive

System functioning: These systems do not have sufficient residence time to allow phytoplankton populations to establish and are clear enough to support periphyton growth. The substrate is hard and not optimal for macrophytes. Periphyton, therefore, are the dominant type of producer.

Management considerations: These systems are highly susceptible to inputs that continually enter the system. Periphyton make efficient use of low concentrations of soluble P or N in water. Sediment retention of nutrients will be low so the system should quickly respond to reductions in loading.

Monitoring and further analysis: Input of nutrients via surface and ground water is the critical factor for these systems. However, monitoring is complicated by the removal of nutrients from the water column by periphyton. Loads can be estimated by monitoring water concentrations during periods when algae are not growing. However, the sampling should be as representative as possible of growing season conditions. Ground water concentrations and discharge may be important.

System I—Large stream that shifts between phytoplankton and macrophytes

	Increased loading	Decreased loading
Phosphorus	Moderately sensitive	Insensitive
Nitrogen	Insensitive	Insensitive

System functioning: These systems have sufficient residence time that phytoplankton can become established. If phytoplankton are established they may shade out macrophytes. These systems can be complex and difficult to predict. Temperature can be important. If winter is sufficiently cold, substantial macrophyte dieback could give phytoplankton an advantage. Spring time P concentrations may be a critical factor.

Management considerations: Macrophyte domination may be advantageous for sport fish production.

Monitoring and further analysis: Spring and summer TP concentrations can be monitored along with macrophyte abundance to determine the extent that phytoplankton production might be controlled through reduction of P loading.

System J—Large stream that shifts between phytoplankton and periphyton

	Increased loading	Decreased loading
Phosphorus	Sensitive	Sensitive
Nitrogen	Insensitive	Insensitive

System functioning: These systems have sufficient residence time that phytoplankton can become established. The substrate is not suitable for macrophytes so periphyton are expected. If phytoplankton are established, they may shade out periphyton.

Management considerations: If soft sediment is not prevalent, the system may have low internal loads (sediment memory) and respond quickly to nutrient load reductions.

Monitoring and further analysis: During periods of phytoplankton domination (indicated by reduced water clarity or greenish color), water column TP can be monitored to estimate loading rate. Nongrowing season monitoring of TP can also be used to estimate growing season loading. However, the sampling should be as representative as possible of growing season conditions. Ground water inputs may be significant.

System K—Oligotrophic or mesotrophic deep lake or reservoir

	Increased loading	Decreased loading
Phosphorus	Highly sensitive	Insensitive (if oligotrophic) Sensitive (if mesotrophic)
Nitrogen	Insensitive	Insensitive

System functioning: These lakes are deep enough to strongly stratify, yet the oxygen demand within the hypolimnion and sediment is not sufficiently large to deplete all of the DO within the hypolimnion. Because the hypolimnion remains oxic, P within the sediment stays bound. Nutrient loading to these lakes is already low to moderate, which supports a mesotrophic or oligotrophic state.

Management considerations: These systems are extremely sensitive to increases in P loading. A small increase in algal production may be sufficient to deplete hypolimnetic DO, which would release sediment-bound P. This P would make its way into the epilimnion either through diffusion or during turnover. The additional internal loading combined with the continuing external loading would move the lake into a eutrophic or hypereutrophic state.

Monitoring and further analysis: Total P and Secchi depth should be monitored regularly. Watershed loading models can help identify loading sources and critical areas. Total P inputs of major streams can be monitored.

System L—Estuary

	Increased loading	Decreased loading
Phosphorus	Insensitive	Insensitive
Nitrogen	Sensitive	Sensitive

System functioning: Estuaries have sufficient P supplied from marine water and from rapid cycling through sediment in most cases, although exceptions have been found. Denitrification (reduction of nitrate to gaseous forms that are lost to the atmosphere) occurs in the sediment so N is frequently the limiting nutrient for aquatic plant growth.

Management considerations: Estuaries respond to reduced N loading rates.

Monitoring and further analysis: Estuarine dynamics are complex. The sensitivity and responsiveness to N loading changes depend on circulation patterns, mixing patterns, and several other factors. Monitoring N loading from tributaries, atmospheric sources, and ground water is important for refining management plans.

System M—Stratified deep lake with hypolimnetic P transfer

	Increased loading	Decreased loading
Phosphorus	Moderately sensitive	Insensitive
Nitrogen	Insensitive	Insensitive

System functioning: These lakes are mesotrophic, eutrophic, or hypereutrophic. They stratify, and P concentrations build up in the anoxic/anaerobic hypolimnion. A fair amount of hypolimnetic P is transferred to the epilimnion because of wind-induced turbulence.

Management considerations: These systems are extremely difficult to restore. Aggressive measures, such as P inactivation by chemical treatments and hypolimnetic aeration, may be needed.

Monitoring and further analysis: Careful analysis by a professional limnologist is advised to determine what combination of load reductions and in-lake treatments will be successful.

System N—Stratified deep lake

	Increased loading	Decreased loading
Phosphorus	Sensitive	Insensitive
Nitrogen	Insensitive	Insensitive

System functioning: These lakes can be oligotrophic, mesotrophic, eutrophic, or hypereutrophic. The hypolimnetic P transfer is less than that in system M lakes. Because of this, external loads from surface water inputs are relatively more important. Because the hypolimnion becomes anoxic during part of the year, internal P loading occurs. This released P is not available to algae until it reaches the photic zone, often during turnover.

Management considerations: P loading needs to be reduced to prevent further eutrophication in these lakes. The response to load reductions depends on the relation between internal load and external load and the history of sediment P loading.

Monitoring and further analysis: Monitor TP through the year, particularly during turnover events. Estimates of surface water P loading rates are useful.

System O—Polymictic lake

	Increased loading	Decreased loading
Phosphorus	Sensitive if mesotrophic/oligotrophic Insensitive if highly eutrophic (TP >50 ug/L)	Sensitive if mesotrophic/oligotrophic Insensitive if highly eutrophic (TP >50 ug/L)
Nitrogen	Insensitive (sensitive if hypereutrophic)	Insensitive

System functioning: Polymictic lakes experience short-term stratification. If they are currently at a mesotrophic or oligotrophic state, they are sensitive to increases in P loading. The risk is when the bottom water goes anaerobic during the usually short periods of stratification. When that happens, P is released from the sediment and the frequent mixing events deliver P to the epilimnion. In cases where the bottom water goes anaerobic, internal P loading rates can be very high, producing a hypereutrophic condition in which N might be limiting. In such cases blooms of N_2-fixing cyanobacteria may dominate the algal community.

Management considerations: The current condition of the lake dictates sensitivity. If the lake is mesotrophic or oligotrophic, it is extremely vulnerable to increased P loadings. If the lake is eutrophic, it is difficult to alter the trophic state because of the high internal loading rate. If the lake is highly eutrophic (TP >50 ug/L) algae are most likely light limited and may not respond to further increases in P loading.

Monitoring and further analysis: If the lake is highly eutrophic, careful analysis by a professional limnologist is advised to determine what combination of load reductions and in-lake treatments will be successful.

System P—Shallow lake with high macrophyte coverage

	Increased loading	Decreased loading
Phosphorus	Sensitive	Insensitive
Nitrogen	Insensitive	Potentially sensitive

System functioning: These lakes are macrophyte dominated (at least 50 percent of surface area). Shallow lakes have two alternative stable states—phytoplankton-dominated or macrophyte-dominated. Macrophytes are beneficial in these systems. They keep sediment from being suspended and, therefore, help keep nutrient levels in the water column low. Macrophytes keep the water clear and protect zooplankton that graze on phytoplankton. They provide habitat for sport fish, such as bass. If the macrophytes are removed or if P loading increases, the system could be shifted to phytoplankton-dominated. In this state, macrophytes cannot reestablish because of shading by phytoplankton. The sediment (and associated P) is vulnerable to resuspension from wind-induced turbulence or from bioturbation (bottom-feeding fish stirring up the sediment). Sport fish populations decline. These systems may be N-limited because the macrophytes can get sufficient P from sediment while denitrification is occurring within the sediment.

Management considerations: In these systems it is practically impossible to get rid of the aquatic "weeds" and not have phytoplankton take over. Conditions under phytoplankton domination would be less suitable for human use (there would be reduced fishing, tainted fish flesh, reduced water clarity, and a higher trophic state). The macrophytes should be accepted as beneficial in these systems.

Monitoring and further analysis: Secchi depth or chlorophyll-a monitoring in the open part of the lake provides early warning if the lake begins to shift from macrophyte domination to phytoplankton domination.

System Q—Shallow lake with low macrophyte coverage

	Increased loading	Decreased loading
Phosphorus	Insensitive	Insensitive
Nitrogen	Insensitive	Insensitive

System functioning: Refer to the description of system P. System Q is the other alternate stable state for this type of lake. High P concentrations result from resuspension of sediment. External loading rates have little effect.

Management considerations: Converting this system to macrophyte domination would be beneficial. However, attempts by researchers and lake managers to accomplish this shift have had mixed results. Temporary elimination of bottom feeding fish may be necessary.

Monitoring and further analysis: An estimate of external and internal loading (calculated from mass balance) is useful to assist in analysis by a professional limnologist.

System R—Shallow lake with short residence time and high turbidity

	Increased loading	Decreased loading
Phosphorus	Insensitive	Insensitive
Nitrogen	Insensitive	Insensitive

System functioning: This system does not have sufficient residence time to permit phytoplankton to establish and, because of high turbidity, is light limited.

Management considerations: If the turbidity levels were reduced, periphyton and/or macrophytes will establish.

Monitoring and further analysis: Watershed loading models can be used to identify sources of turbidity and nutrients and to evaluate mitigation alternatives.

Next steps

The procedure described in this document is a screening level analysis. In many cases the results of this analysis are sufficient for the management needs at hand. In other situations a more thorough analysis of the waterbody and its watershed may be necessary or advisable.

The next steps a conservationist might take are described in this section. This section is organized into three subsections as follows:

- Gaining more knowledge or professional assistance
- Obtaining more information about the waterbody and watershed
- Using computer-based analysis tools

Gaining more knowledge or professional assistance

Undertaking a more thorough analysis of the response of a waterbody to changes in nutrient loading requires a basic understanding of limnology and aquatic ecology. The interrelationship of chemical, physical, and biological processes in aquatic ecosystems is a fascinating topic. Conservationists who are intrigued by what they have learned as a result of using the procedure in this document should consider further reading in limnology and aquatic ecology. The following books and papers are recommended.

Texts and manuals:

United States Environmental Protection Agency. 1988. The lake and reservoir restoration guidance manual. EPA 440/4-90-006. Available from NCEPI, 11029 Kenwood Road Building 5, Cincinnati, OH 45242, Fax 513-489-8695, and from the EPA Clean Lakes Web site at www.epa.gov/owowwtr1/lakes/quality.html

Moss, Brian. 1998. Ecology of fresh waters: man and medium, past to future. Blackwell Science, Malden, MA, 557 p.

Welch, E.B. 1992. Ecological effects of wastewater: applied limnology and pollution effects, 2nd ed. Chapman and Hall.

Cooke, G.D., E.B. Welch, S.A. Peterson, and P.R. Newroth. 1993. Restoration and management of lakes and reservoirs. Lewis Publishers: Boca Raton, FL.

General eutrophication reviews:

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications 8:559-568.

Correll, D.L. 1998. The role of phosphorus in the eutrophication of receiving waters: a review. J. Env. Qual. 27:261-266.

Smith, V.H. 1998. Cultural eutrophication of inland, estuarine, and coastal waters. *In* (M.L. Pace and P.M. Groffman, eds.) Successes, limitations, and frontiers in ecosystem science. Springer-Verlag, New York, p. 7– 49.

Rivers and streams:

Dodds, W.K., V. H. Smith, and B. Zander. 1997. Developing nutrient targets to control benthic chlorophyll levels in streams: a case study of the Clark Fork River. Water Research 31:1738-1750.

Dodds, W.K., J.R. Jones, and E.B. Welch. 1998. Suggested classification of stream trophic state: distributions of temperate stream types by chlorophyll, total nitrogen, and phosphorus. Water Research 32:1455-1462.

If the resource management situation is particularly complex or involves costly management alternatives (and if funds are available), a professional limnologist should be consulted. A professional limnologist is able to efficiently conduct an assessment, develop a plan for monitoring if necessary, and develop management alternatives and recommendations. The North American Lake Management Society maintains a listing of Certified Lake Managers and has local chapters in most States that can provide assistance in locating a professional limnologist (visit their Web site at www.nalms.org). Engineering firms in your state may have specialized expertise in limnological analyses. Review the credentials of a prospective consultant and reports from similar studies they have completed. Talk with their previous clients and with others in a position to offer a recommendation, such as state agency and university scientists.

Obtaining more information

To conduct a more thorough analysis, additional information will most likely be needed. Information generally falls into two categories—information about the waterbody and information about the watershed.

Information about the waterbody encompasses waterbody characteristics, such as physical dimensions and configuration; seasonal patterns of water temperatures and stratification; spatial and temporal patterns of oxygen, phosphorus, chlorophyll, and nitrogen concentrations; and areal extent of macrophyte beds. Information about the watershed includes land use, hydrology, nutrient loads, and other information related to sources of nutrients.

The information to be collected should be guided by the analyses that will be conducted. For example, to evaluate source contributions from different areas, data on land use are needed, and, if models are used, data on soils, slopes, and crops may be required. To assess the current internal and external phosphorus loading rates, tributary phosphorus concentrations, lake TP concentrations, and hypolimnetic DO and TP concentrations are needed.

Some information requires data collected through a monitoring system. It is critically important that a monitoring system be carefully designed. Key aspects of monitoring system design follow:

Monitoring objective—A successful monitoring system requires a clear, concise objective statement and that the monitoring system be designed to address that objective with statistical rigor. A monitoring system designed to address a narrow, specific objective is more likely to be successful than unfocused monitoring.

Statistical considerations—Part of the design of a monitoring system is identifying the statistical analyses that will be used to interpret the data and ensuring that the design collects the correct types of data and enough data to support the analyses with a known level of statistical confidence.

Quality assurance/quality control—Without careful attention to quality assurance/quality control (QA/QC), the data may be unusable. QA/QC measures must be established, and they must be followed. Standard operating procedures for both the field and the laboratory, use of field blanks/replicates/spikes, sample chain of custody, analysis methods, and lab QA are just a few of the aspects of QA/QC that should be considered.

Data management—Data entry is a common source of errors. Error checking within the data entry program and double data entry are recommended. Data should be reviewed and analyzed on a regular basis, preferably quarterly, to spot any potential problems in the monitoring system operation.

Several useful manuals are available to assist in the design and implementation of a monitoring system. They include:

United States Department of Agriculture, Natural Resources Conservation Service. 1996. National handbook of water quality monitoring. 450-vi-NHWQM, December 1996. National Water and Climate Center, Portland, Oregon.

United States Environmental Protection Agency. 1990. Monitoring lake and reservoir restoration. EPA 440-4-90-007.

United States Environmental Protection Agency. 1991. Volunteer lake monitoring: a methods manual. EPA 440/4-91-002.

United States Environmental Protection Agency. 1993. Statistical methods for the analysis of lake water quality trends. EPA 841-R-93-003.

United States Environmental Protection Agency. 1996. The volunteer monitor's guide to quality assurance project plans. EPA 841-B-96-003.

United States Environmental Protection Agency. 1997. Volunteer stream monitoring: a methods manual. EPA 841-B-97-003.

Computer-based planning tools

Computer-based planning tools are available to help estimate loadings generated within a watershed or predict responses within an aquatic system. These tools rely on models of physical, chemical, and biological processes. Models are mathematical simplifications designed to describe the behavior of complex systems. If a model can accurately capture the most important processes occurring in a system, it can be used to both describe the system and predict its behavior. Models are also useful as a means of assembling important information and as an aid to diagnosis and planning.

Models vary greatly in their complexity. A good overview of models was provided by EPA (1992). Simple models require the least effort to set up and use, but they frequently require data or empirical relationships

specific to a type of situation or local region. Simple models are compilations of expert judgment and empirical relationships that can often be applied by using a spreadsheet program or handheld calculator. They rely, in general, on large-scale aggregation and neglect important features of small patches of land. They rely on generalized sources of information and, therefore, have low requirements for site-specific data. Predictive relationships are derived from empirical relationships that are based on regional or site-specific data. Outputs are generally expressed as mean annual values.

Mid-range models attempt a compromise between the empiricism of simple models and the complexity of detailed mechanistic models. The advantage of mid-range models is that they evaluate pollution sources over broad geographic scales with greater resolution and can be used to target conservation efforts. Several mid-range models are designed to interface with a geographic information system (GIS), which greatly facilitates input parameter estimation. Greater use of site-specific input data compared to simple models gives these models relatively broad applicability in different regions. However, the use of simplifying assumptions limits the accuracy of their predictions to within about an order of magnitude and restricts their usefulness to relative comparisons of scenarios.

Complex models best represent the current understanding of watershed and water quality processes. Because they attempt to simulate the specific mechanisms that drive processes, they are called mechanistic or process-based models. If properly applied and calibrated, complex models can provide relatively accurate predictions of variable flows, pollutant concentrations, and water quality anywhere in the watershed. The greater resolution and accuracy comes at the expense of considerably more time and resource expenditure. These models must generally be applied by highly skilled specialists. The input and output of complex models have greater spatial and temporal resolution. Because of their focus on processes, they can be used to predict the effects of different design considerations for practices.

Table 4 lists several commonly used watershed or waterbody models in order of their complexity. It is important that any user understand the benefits and limitations of a given model for his or her question. A brief description of each model follows.

Table 4 Comparisons of model types for P and N nonpoint source pollution

User resources	Simple				Midrange				Complex			
Setup time	Minimal								Significant			
Monitoring data	Usually not required								Required			
Time step	Typically annual								Daily/hourly			
Equations/algorithms	Empirical								Process-based			
Input data required	Few parameters								Many parameters			
Model name	WILMS	EUTROMOD	BATHTUB	WEND	GWLF	SWAT	BASINS	AGNPS	SWMM	ANSWERS	HSPF	WEPP
Model type [1/]	L, W	L, W	W	L	L	L, W	L, W	L	L	L	L, W	L

1/ L = watershed loading model; W = water quality response model.

Simple models:

WILMS (Wisconsin Lake Model Spreadsheet)
A spreadsheet-based procedure developed using regression equations developed from international lake data sets. Watershed loads are estimated using watershed area in different land uses and export coefficients. Lake response is based on empirically derived response models. Ten lake response models are available to predict spring overturn and growing season mean TP concentrations. The procedure provides parameter range guidance to help the user select a lake response model and also includes an uncertainty analysis, watershed load back-calculation, lake condition description, and a phosphorus steady state response time estimate (Panuska, et al., 1994).

Available at www.nalms.org.

EUTROMOD
A spreadsheet-based modeling procedure for eutrophication evaluation developed at Duke University and distributed by the North American Lake Management Society. EUTROMOD is a watershed and lake model designed to estimate nutrient loadings and the resulting trophic state parameters. The parts of a watershed area in different land use categories are the basis for estimating nutrient exports. Computation algorithms were developed based on empirically derived statistical relationships. At the present time the model is specific to the southeastern United States.

Available at www.nalms.org.

BATHTUB
One of a suite of three simplified models developed by the Corps of Engineers. The suite focuses on lake and reservoir response and not on watershed loading estimation. The interrelated programs (FLUX, PROFILE, and BATHTUB) simplify assessments of eutrophication-related processes and effects. FLUX allows estimation of tributary mass discharges (loadings) from sample concentration data and daily flow records. Five estimation methods are available, and potential errors in estimates are quantified. PROFILE facilitates the analysis of in-lake water quality data. Algorithms are included for calculation of hypolimnetic oxygen depletion rates and estimation of area-weighted, surface-layer mean concentrations of nutrients, and other eutrophication response variables. BATHTUB applies a series of empirical eutrophication models to morphologically complex lakes and reservoirs. The program performs steady-state water and nutrient balance calculations in a spatially segmented hydraulic network that accounts for advective and diffusive transport and nutrient sedimentation. Eutrophication-related water quality conditions (total phosphorus, total nitrogen, chlorophyll-a, transparency, and hypolimnetic oxygen depletion) are predicted using empirical relationships derived from reservoir data.

Available from the Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, Mississippi 39180. Web site at www.wes.army.mil/el/elmodels/emiinfo.html.

WEND (Watershed Ecosystem Nutrient Dynamic)
A watershed-scale phosphorus budget model that simulates the generation of animal wastes, utilization and management, distribution within the watershed, and transfer to watercourses. The model identifies and quantifies pathways of all significant P import, export, and internal cycling fluxes on an average annual basis. Evaluations can be conducted for a variety of management scenarios to simulate changes in watershed P dynamics over long time periods. WEND emulates the infrastructure through which P is stored and cycled in a watershed and must be tailored to reflect watershed differences. The model operates in STELLA, an object oriented programming language. Planned enhancements include nitrogen fluxes and pathogen dynamics.

Available from Alan Cassell, School of Natural Resources, Aiken Hall, University of Vermont, Burlington, VT 05405-0088, ecassell@zoo.uvm.edu. STELLA™ is required and can be purchased from: High Performance Systems, Inc., 45 Lyme Rd., Suite 200, Hanover, NH 03755 (800) 332-1202. Web site at www.hps-inc.com.

Mid-range models:

GWLF (Generalized Watershed Loading Function)
A mid-range model developed at Cornell University to address P and N loading from large mixed land use watersheds (Haith and Shoemaker, 1987; Dodd and Tippett, 1994). Based on loading functions to estimate nutrient loads produced by a watershed. Loading functions represent a middle ground between the empiricism of export coefficients and the complexity of chemical simulation models. GWLF was developed with the expressed purpose of requiring no calibration and makes extensive use of default parameters.

An enhanced version was developed by the Research Triangle Institute in FoxPro for Windows.™ Contact Michael McCarthy, Research Triangle Institute, P.O. Box 12194, Research Triangle Park, NC 27709, (919) 541-6895.

SWAT (Soil and Water Assessment Tool)
Designed to predict the effect of management decisions on water, sediment, nutrient, and pesticide yields with reasonable accuracy in large, ungaged river basins. Nutrients and pesticides are considered for pollutant transport. Sediment transport and deposition through ponds, reservoirs, and channels is modeled. Nutrient transformations are not evaluated.

Supported by the USDA Agriculture Research Service, Grassland Soil and Water Research Laboratory, 808 E. Blackland Rd., Temple, TX 76502, Phone: (254) 770-6500. Visit their Web site at www.brc.tamus.edu/swat/.

BASINS
A relatively user-friendly package developed by the EPA in which key data and analytical components are brought together in one CD. Data include STORET water quality data and other environmental data, point sources information, and various GIS layers. Analysis tools are grouped into five categories:

- national data bases
- assessment tools (TARGET, ASSESS, and Data Mining)
- utilities including local data import, land-use and DEM reclassification, watershed delineation and management of watershed delineation, and management of water quality observation data
- watershed and water quality models including a nonpoint source screening model (based on HSPF), TOXIROUTE, and Qual2E
- post-processing output tools for interpreting model results

Data bases and assessment tools are directly integrated within an ArcView™ GIS environment. The simulation models run in a Windows™ environment, using data input files generated in ArcView.

Available free of charge from the USEPA on the Web at www.epa.gov/OST/BASINS. ArcView 3.x is required.

AGNPS98 - AGNPS
AGNPS was originally developed as a single event model to predict the amount of runoff, sediment, and nutrients produced by farmland during a storm event. It has been used widely in the Midwest. A grid cell system is used to represent the spatial distribution of watershed properties. Model output includes runoff, sediment, nutrients, and pesticide loads although there is no chemical transformation of P or N. AGNPS98 is an upgraded version running in a continuous simulation mode. Data input is time consuming although a GIS interface is planned.

Available from the USDA Agriculture Research Service, National Sedimentation Laboratory, Oxford, Mississippi. Web site at www.sedlab.olemiss.edu/AGNPS98.

Complex models:

SWMM (Storm Water Management Model)
A detailed watershed model originally designed to address urban stormwater hydrology. A large, complex model capable of simulating the movement of precipitation and pollutants from the surface through pipe and channel networks, storage/treatment units, and finally to receiving water. Both single-event and continuous simulation may be performed on catchments having storm sewers and natural drainage for prediction of flows, stages, and pollutant concentrations. Can be used for both planning and design. The planning model is used for an overall assessment of urban runoff and proposed abatement options. A design-level, event simulation also may be run using a detailed catchment schematization and shorter time steps for precipitation input. Data intensive and requires calibration and validation. Main utility is for urban areas where the design of pollution control structures is part of the study.

Available from the USEPA, Environmental Research Laboratory, Athens, Georgia. Web site at http://www.epa.gov/CEAM.

ANSWERS (Areal Nonpoint Source Watershed Environmental Response Simulation Model)
A comprehensive model to evaluate the effects of land use management in both agricultural and urban watersheds. Focuses on sediment erosion and transport during storm events. A mainframe computer is required, there are no chemical transformations of N or P, and building input files is complex and time consuming.

Distributed by the Department of Agriculture Engineering, North Carolina State University, Raleigh, North Carolina, (919) 515-2694.

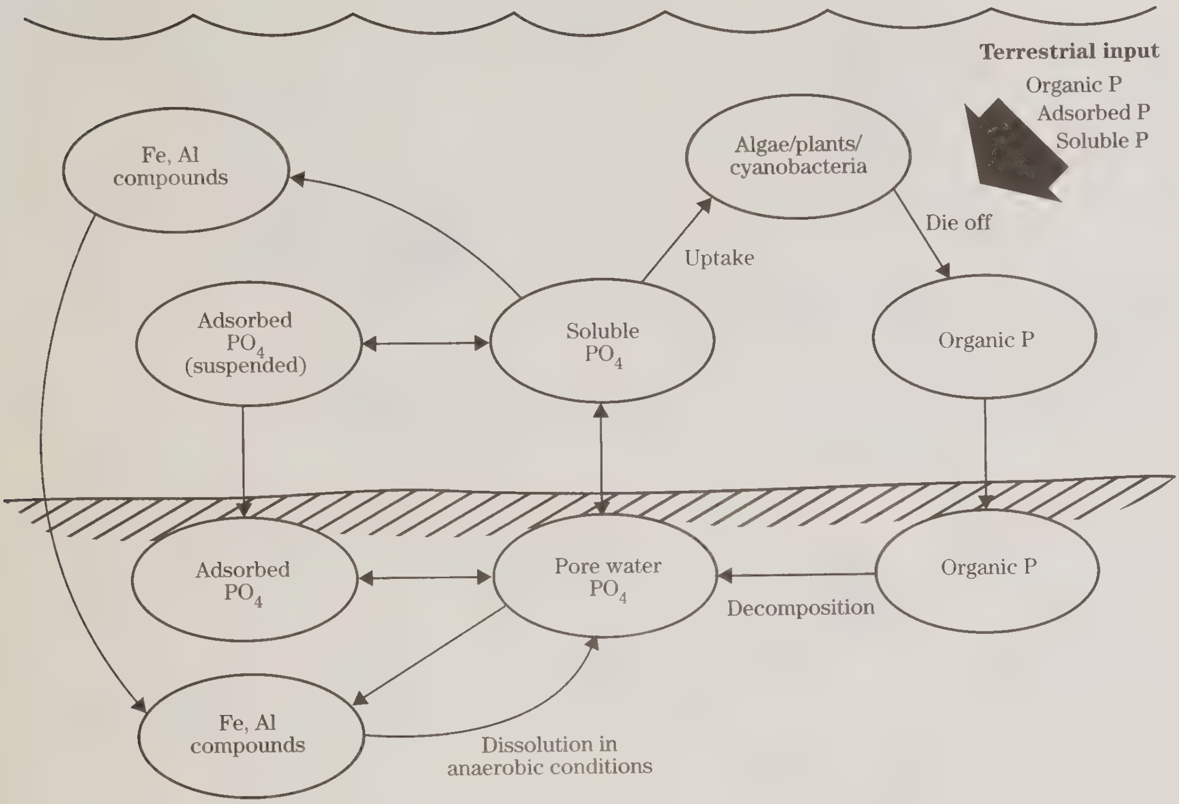
HSPF (Hydrological Simulation Program-FORTRAN)
A comprehensive modeling package developed by the EPA to simulate hydrology and pollutant fate in complex watersheds. Extensive monitoring data are needed for calibration. Requires highly trained staff.

Supported by USEPA, Environmental Research Laboratory, Athens, Georgia. Web site at http://www.epa.gov/CEAM.

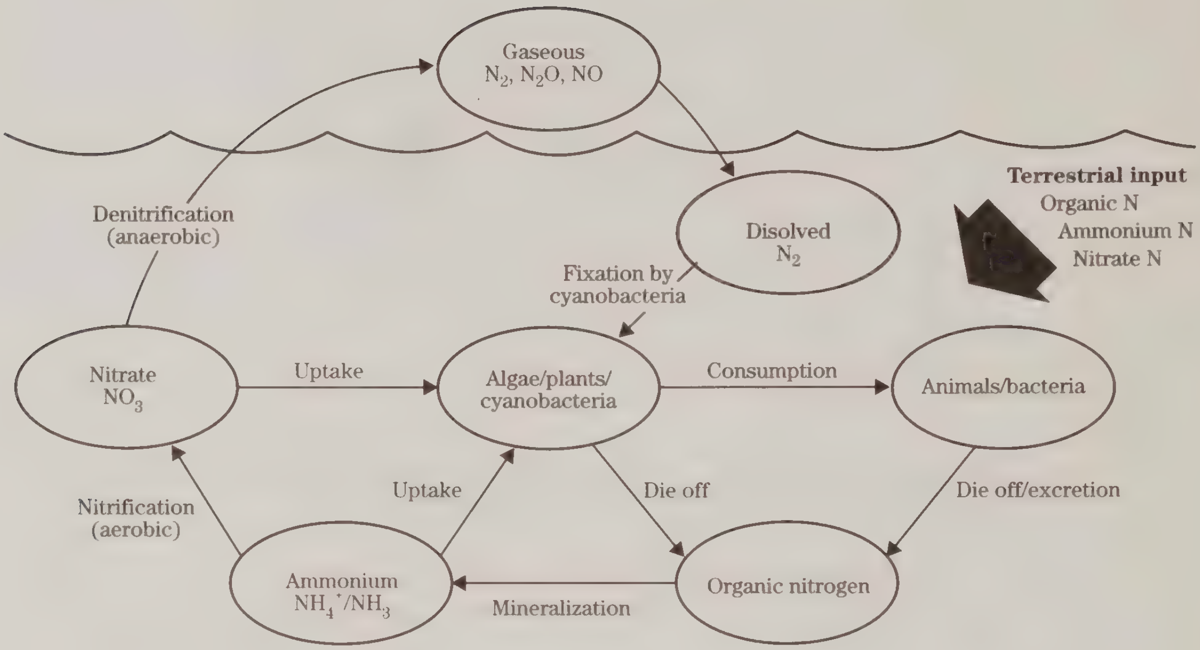
WEPP (Water Erosion Prediction Project)
Process-based, distributed parameter, continuous simulation, erosion prediction model for use on personal computers. Does not simulate nutrient transport. Current version (v98.4) available through the Internet is applicable to hillslope erosion processes (sheet and rill erosion) as well as simulation of the hydrologic and erosion processes on small watersheds.

Supported by USDA Agriculture Research Service, National Sedimentation and Erosion Laboratory, 1196 Building SOIL, Purdue University, West Lafayette, Indiana 47907-1196, (765) 494-8673. Web site at http://topsoil.nserl.purdue.edu/weppmain/wepp.html.

Appendix A Phosphorus cycle in aquatic ecosystems



Appendix B Nitrogen cycle in aquatic ecosystems



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Glossary

Aerobic Describes life or processes that require the presence of molecular oxygen.

Algae Small aquatic plants that occur as single cells, colonies, or filaments.

Anaerobic Describes processes that occur in the absence of molecular oxygen.

Anoxia A condition of no oxygen in the water. Often occurs near the bottom of fertile stratified lakes in the summer and under ice in late winter.

Autotrophic Ability to synthesize organic compounds from inorganic substrates, using light energy (photoautotrophs) or chemical energy (chemoautotrophs).

Bathymetric map A map showing the bottom contours and depth of a lake. Can be used to calculate lake volume.

Biomass The mass of living organisms present in a waterbody at any one time; the result of processes of growth and death in the system.

Chlorophyll-*a* A type of chlorophyll present in all types of algae, sometimes in direct proportion to the biomass of algae.

Dissolved oxygen Gaseous oxygen in an aqueous solution. Expressed as milligrams O_2 per liter of water. The saturation concentration decreases with increasing temperature. At 20 degrees Celsius and 1 atmosphere, the saturation concentration is 9.09 mg/L.

Epilimnion Uppermost, warmest, well-mixed layer of a lake during summertime thermal stratification. The epilimnion extends from the surface to the thermocline.

Eutrophic From Greek for "well nourished," describes a lake of high photosynthetic activity and low transparency.

Eutrophication The process of physical, chemical, and biological changes associated with nutrient, organic matter, and silt enrichment and sedimentation of a lake or reservoir. If the process is accelerated by human influences, it is termed cultural eutrophication.

Fetch Length of lake or reservoir surface for wind to act upon; in general, the longer the fetch, greater the possibility of wind effects on mixing.

Heterotrophic Ability to obtain energy through the use of organic compounds produced by other organisms.

Hypolimnion Lower, cooler layer of a lake during summertime thermal stratification.

Lentic Relating to standing water.

Limnology Scientific study of fresh water, especially the history, geology, biology, physics, and chemistry of lakes. Also termed freshwater ecology.

Littoral zone That part of a waterbody extending from the shoreline to the greatest depth occupied by rooted plants.

Lotic Relating to running water.

Macrophytes Rooted and floating aquatic plants visible to the naked eye or larger than 0.5 millimeters. These plants may flower and bear seed. Some forms are free-floating without roots.

Mesotrophic Describes a waterbody of moderate plant productivity and transparency.

Metalimnion Layer of rapid temperature and density change in a thermally stratified lake. Resistance to mixing is high in the region.

Nitrogen An element essential to life. Occurs in water in various forms. The forms most useful to organisms are organic nitrogen, nitrate (NO_3^-), and ammonia/ammonium (NH_3/NH_4^+). Aqueous concentration is expressed as mg N/L ("nitrate-N," "ammonia-N"), which means expressed as the mass of N (atomic weight 14) and not the mass of nitrate or ammonia.

NTU Nephelometric turbidity unit. A measure of the scattering of light by particles suspended within a water sample.

Nutrient An element or chemical essential to life.

Oligotrophic From the Greek for "poorly nourished," describes a lake of low plant productivity and high transparency.

Periphyton Complex assemblage of autotrophic and heterotrophic organisms attached to submerged substrates and embedded in a polysaccharide matrix.

pH Refers to the power of hydrogen ion concentration in an aqueous solution and is the negative log of the concentration of hydrogen ions. For example, pH = 7 means the concentration of H^+ ions is 10^{-7} moles/liter. Values ranges from pH=1 (very acidic) to pH=14 (very basic). pH of 7 is neutral and most surface water ranges between pH values of 6 and 9.

Phosphorus An element essential for life. Occurs in water in various forms. The forms most useful to organisms are organic P and orthophosphate. Concentration of orthophosphate is often expressed as mg PO_4–P/L; this means the form is PO_4, but the reported mass is based on P (atomic weight 31).

Photic zone The lighted part of a lake where photosynthesis takes place. Extends down to a depth where photosynthesis and respiration are balanced by the amount of light available.

Phytoplankton Microscopic algae and microbes that float freely in open water.

Plankton Organisms that float freely in the water and are not attached to a substrate.

Primary productivity The rate at which algae and macrophytes fix or convert carbon dioxide to sugar in plant cells. Commonly measured as milligrams of carbon per square meter per hour.

Residence time Commonly called the hydraulic residence time; the amount of time required to completely replace the volume of water in a waterbody with an equal volume of "new" water.

Respiration Process by which organic matter is oxidized by organisms. The process releases energy, carbon dioxide, and water.

Riparian The zone adjacent to a stream or any other waterbody (from the Latin word *ripa*, pertaining to the bank of a river, pond, or lake).

Secchi depth A measure of the transparency of water obtained by lowering a black and white disk of 20 cm diameter into water until it is no longer visible. Expressed in units of depth.

Stratification Layering of water caused by differences in water density.

Thermal stratification Stratification caused by temperature-created differences in water density.

Thermocline A horizontal plane across a waterbody at the depth of the most rapid vertical change in temperature. See Metalimnion.

Trophic state The degree of nutrient enrichment of a waterbody.

Turnover The mixing of bottom and surface water following the breakup of stratification in lakes and reservoirs.

Water column Water in a waterbody between the interface with the atmosphere at the surface and the interface with the sediment at the bottom. Concept derives from vertical series of measurements used to characterize lake water.

Zooplankton Microscopic animals that float freely in lake water, graze on detritus particles, bacteria, and algae, and may be consumed by fish.